Beamforming Cancellation Design for Millimeter-Wave Full-Duplex

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Outline

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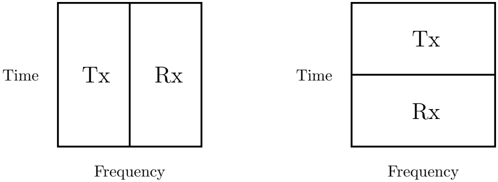
Problem Statement & Motivation

Conventionally, radios operate in a half-duplex fashion to avoid the prohibitive **self-interference**.



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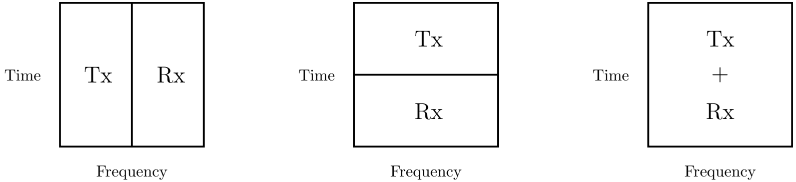

mmWave full-duplex:

- transmission and reception on the same mmWave time-frequency resource.

Problem Statement & Motivation

Why do we care about full-duplex at mmWave?

- increased spectral efficiency
- lower latency
- enable smarter networks
- deployment solution for mmWave networks
- opportunity to redesign conventional half-duplex applications at mmWave
- extends to mmWave communication and radar coexistence
- . . .

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Full-duplex has been well-explored at sub-6 GHz.

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Dense antenna arrays at mmWave offer a promising means for further self-interference mitigation.

- spatial self-interference mitigation

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Dense antenna arrays at mmWave offer a promising means for further self-interference mitigation.

- spatial self-interference mitigation $\rightarrow$ "beamforming cancellation"

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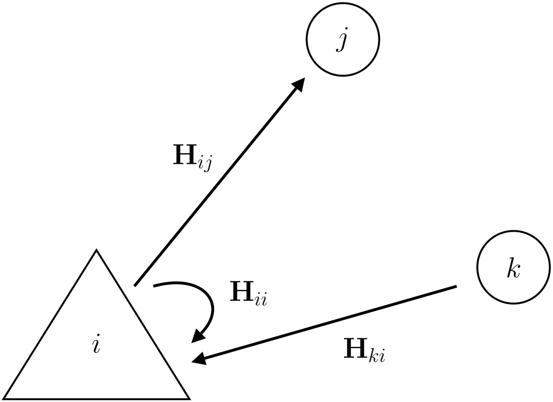

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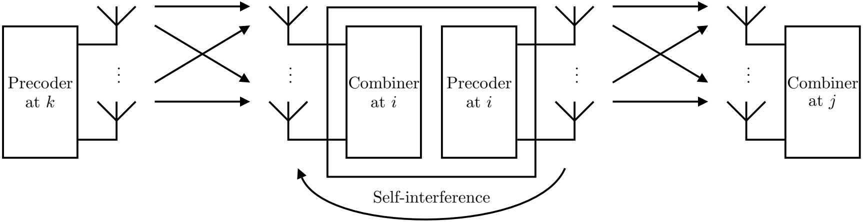

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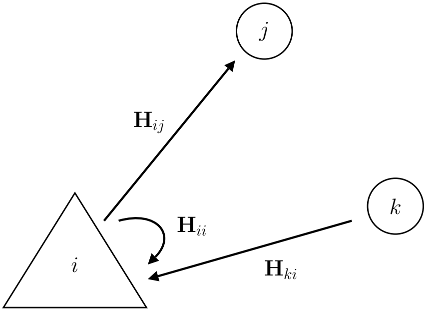

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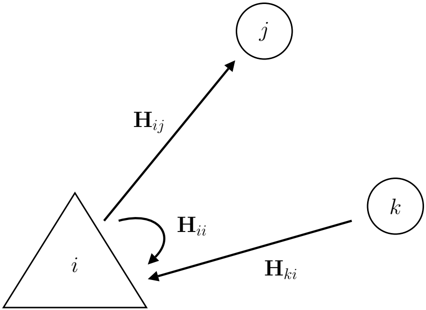

We seek a beamforming (precoding and combining) design that:

- successfully communicates from i to j.
- successfully communicates from k to i.
- mitigates the self-interference at i.

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Not the goal of this work:

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Our design is based largely on several assumptions. A practical design would deviate from this.

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Proposed Design

We consider mmWave radios employing fully-connected hybrid analog/digital beamforming.

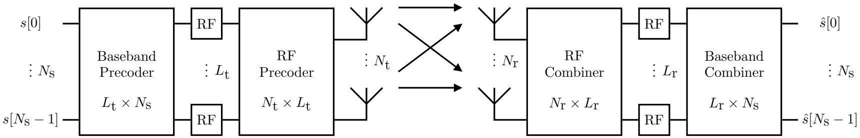


Figure 1: Hybrid beamforming architecture used at mmWave.

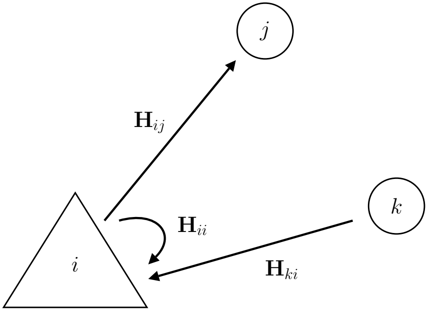
We assume the radio frequency (RF) beamformers have phase control but lack amplitude control.

Proposed Design

Precoders: $\mathbf{F}_{\mathrm{BB}}^{(i)}$, $\mathbf{F}_{\mathrm{RF}}^{(i)}$, $\mathbf{F}^{(k)}$

Combiners: $\mathbf{W}_{\mathrm{BB}}^{(i)}$, $\mathbf{W}_{\mathrm{RF}}^{(i)}$, $\mathbf{W}^{(j)}$

Channels: $\mathbf{H}_{ij}$, $\mathbf{H}_{ki}$, $\mathbf{H}_{ii}$



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How do we model the self-interference channel?

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$$\mathbf{H}_{\mathrm{SI}} = \sqrt{\frac{\kappa}{\kappa+1}}\mathbf{H}_{\mathrm{SI}}^{\mathrm{LOS}} + \sqrt{\frac{1}{\kappa+1}}\mathbf{H}_{\mathrm{SI}}^{\mathrm{NLOS}} \quad (1)$$

where

- $\kappa \rightarrow$ Rician factor
- $\mathbf{H}_{\mathrm{SI}}^{\mathrm{LOS}} \rightarrow$ spherical wave channel (near-field)
- $\mathbf{H}_{\mathrm{SI}}^{\mathrm{NLOS}} \rightarrow$ Saleh-Valenzuela (ray/cluster)

Proposed Design

Received symbol at the full-duplex node i:

$$\hat{\mathbf{s}}^{(i)} = \sqrt{\mathsf{SNR}_{ki}}\ \mathbf{W}_{\mathrm{BB}}^{*\,(i)} \mathbf{W}_{\mathrm{RF}}^{*\,(i)} \mathbf{H}_{ki} \mathbf{F}^{(k)} \mathbf{s}^{(i)} \quad (2)$$

$$+ \sqrt{\mathsf{SNR}_{ii}}\ \mathbf{W}_{\mathrm{BB}}^{*\,(i)} \mathbf{W}_{\mathrm{RF}}^{*\,(i)} \mathbf{H}_{ii} \mathbf{F}_{\mathrm{RF}}^{(i)} \mathbf{F}_{\mathrm{BB}}^{(i)} \mathbf{s}^{(j)} \quad (3)$$

$$+ \mathbf{W}_{\mathrm{BB}}^{*\,(i)} \mathbf{W}_{\mathrm{RF}}^{*\,(i)} \mathbf{n}^{(i)} \quad (4)$$

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$$+ \mathbf{W}_{\mathrm{BB}}^{*(i)} \mathbf{W}_{\mathrm{RF}}^{*(i)} \mathbf{n}^{(i)} \tag{4}$$

Received symbol at the half-duplex node j:

$$\hat{\mathbf{s}}^{(j)} = \sqrt{\mathsf{SNR}_{ij}}\ \mathbf{W}^{*(j)} \mathbf{H}_{ij} \mathbf{F}_{\mathrm{RF}}^{(i)} \mathbf{F}_{\mathrm{BB}}^{(i)} \mathbf{s}^{(j)} \tag{5}$$

$$+ \mathbf{W}^{*(j)} \mathbf{n}^{(j)}, \tag{6}$$

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We choose to design a zero-forcing solution that completely eliminates the self-interference.

$$\mathbf{W}_{\mathrm{BB}}^{*(i)} \mathbf{W}_{\mathrm{RF}}^{*(i)} \mathbf{H}_{ii} \mathbf{F}_{\mathrm{RF}}^{(i)} \mathbf{F}_{\mathrm{BB}}^{(i)} = \mathbf{0} \tag{7}$$

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Not straightforward, especially with hybrid beamforming.

- hybrid constraints can vary $\rightarrow$ we explore two cases

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Scenario A: design-favorable.

- number of RF chains is twice the number of streams
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Scenario B: more practical.

- number of RF chains is **less than** twice the number of streams
- phase shifters have **finite** precision

Scenario A: $2N_{\mathrm{s}} = N_{\mathrm{RF}}$ & Infinite Resolution Phase Shifters

Proposed Design: Scenario A

The effect of these assumptions is that we can implement any fully-digital beamforming matrix in a hybrid fashion via [1].

$$\mathbf{F} \approx \mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}} \rightarrow \mathbf{F} = \mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}} \tag{8}$$

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This allows us to write

$$\mathbf{W}_{\mathrm{BB}}^{*^{(i)}}\mathbf{W}_{\mathrm{RF}}^{*^{(i)}}\mathbf{H}_{ii}\mathbf{F}_{\mathrm{RF}}^{(i)}\mathbf{F}_{\mathrm{BB}}^{(i)} = \mathbf{0} \tag{9}$$

$$\downarrow$$

$$\mathbf{W}^{*^{(i)}}\mathbf{H}_{ii}\mathbf{F}^{^{(i)}} = \mathbf{0} \tag{10}$$

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More antennas will offer more dimensions for zero-forcing.

Proposed Design: Scenario A

The self-interference channel is not well-characterized at mmWave.

- we assume a Rician combination of a near-field portion and far-field portion

Our design does not rely on its properties; it could very well be full-rank.

- no dimensions for zero-forcing

This motivates us to consider the effective self-interference channel.

- i.e., the portion of $\mathbf{H}_{ii}$ that is **received** by $\mathbf{W}^{(i)}$

Simulation & Results: Scenario A

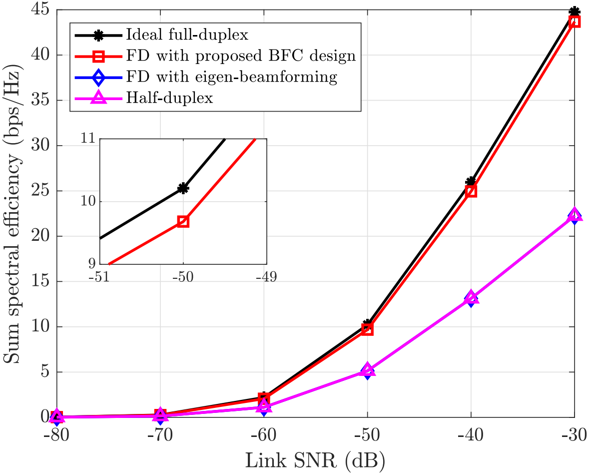

Figure 2: Sum spectral efficiencies achieved in Scenario A with infinite precision phase shifters when $N_{\mathrm{s}} = 3$, $N_{\mathrm{RF}} = 6$, and $N_{\mathrm{t}} = N_{\mathrm{r}} = 16$.

Simulation & Results: Scenario A

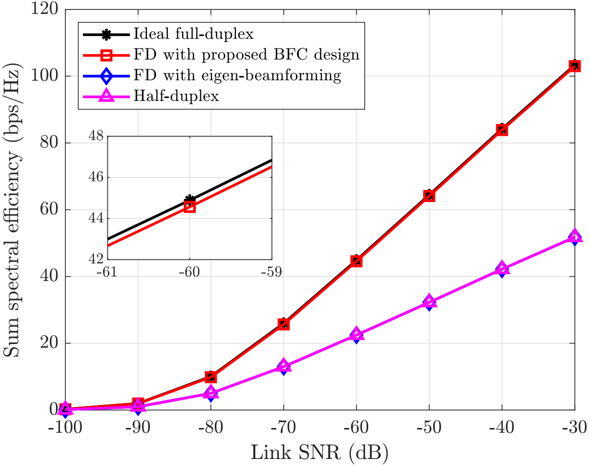

Figure 3: Sum spectral efficiencies achieved in Scenario A with infinite precision phase shifters when $N_{\mathrm{s}} = 3$, $N_{\mathrm{RF}} = 6$, and $N_{\mathrm{t}} = N_{\mathrm{r}} = 64$.

Scenario B: $2N_{\mathrm{s}} > N_{\mathrm{RF}} \geq N_{\mathrm{s}}$ & Finite Resolution Phase Shifters

Proposed Design: Scenario B

The effect of these assumptions is that we cannot necessarily implement any fully-digital beamformer in a hybrid fashion.

We must use some sort of hybrid approximation: $\mathbf{F} \approx \mathbf{F}_{\mathrm{RF}} \mathbf{F}_{\mathrm{BB}}$.

Further, we must ensure that our design holds even with hybrid approximation.

Proposed Design: Scenario B

We initialize both links with hybrid-approximated eigen-beamforming via an orthogonal matching pursuit (OMP) based algorithm [2].

$$[\mathbf{F}_{\mathrm{RF}}, \mathbf{F}_{\mathrm{BB}}] = \mathrm{omp\_decomp}\left(\mathbf{F}, \mathbf{A}_{\mathrm{RF}}, N_{\mathrm{RF}}\right) \tag{11}$$

Deviate the precoder $\mathbf{F}_{\mathrm{BB}}^{(i)}$ by projecting the eigen-beamformer into the null space of ${\mathbf{W}_{\mathrm{BB}}^{*}}^{(i)} {\mathbf{W}_{\mathrm{RF}}^{*}}^{(i)} \mathbf{H}_{ii} {\mathbf{F}_{\mathrm{RF}}^{*}}^{(i)}$.

The self-interference is **completely** mitigated.

What we expect:

· link from i to j is degraded (during projection)

· link from k to i is preserved

More **RF chains** will offer more dimensions for zero-forcing.

Simulation & Results: Scenario B

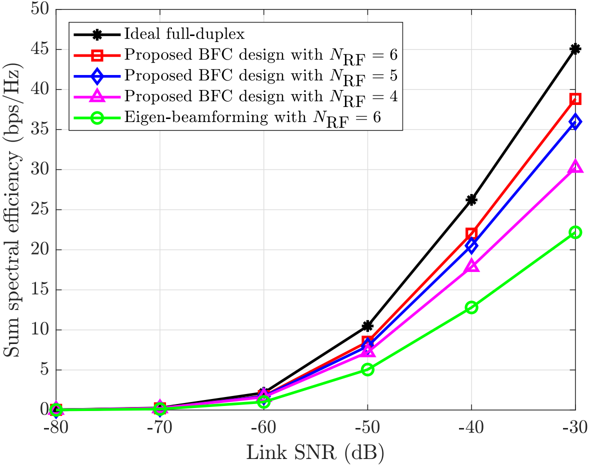

Figure 4: Sum spectral efficiencies achieved in Scenario B with finite precision phase shifters when $N_s = 3$ and $N_t = N_r = 16$.

Simulation & Results: Scenario B

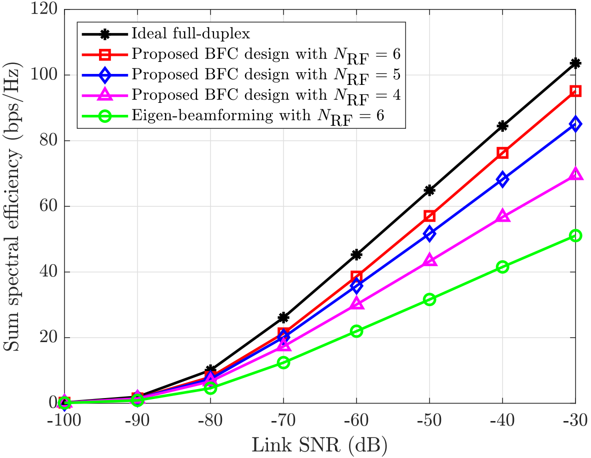

Figure 5: Sum spectral efficiencies achieved in Scenario B with finite precision phase shifters when $N_{\mathrm{s}} = 3$ and $N_{\mathrm{t}} = N_{\mathrm{r}} = 64$.

Thank you. Questions? Feedback?

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References I

[1] F. Sohrabi and W. Yu, "Hybrid digital and analog beamforming design for large-scale antenna arrays," *IEEE Journal of Selected Topics in Signal Processing*, vol. 10, no. 3, pp. 501–513, Apr. 2016.

[2] O. E. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath, "Spatially sparse precoding in millimeter wave MIMO systems," *IEEE Transactions on Wireless Communications*, vol. 13, no. 3, pp. 1499–1513, Mar. 2014.

[3] J. S. Jiang and M. A. Ingram, "Spherical-wave model for short-range MIMO," *IEEE Transactions on Communications*, vol. 53, no. 9, pp. 1534–1541, Sep. 2005.

Bonus

$$\mathbf{H} = \sqrt{\frac{N_{\mathrm{t}} N_{\mathrm{r}}}{N_{\mathsf{rays}} N_{\mathsf{clust}}}} \sum_{m=1}^{N_{\mathsf{clust}}} \sum_{n=1}^{N_{\mathsf{rays}}} \beta_{m,n} \mathbf{a}_{\mathrm{r}}(\theta_{m,n}) \mathbf{a}_{\mathrm{t}}^{*}(\phi_{m,n}) \tag{12}$$

Bonus

$$\mathbf{H}_{\mathrm{SI}} = \sqrt{\frac{\kappa}{\kappa+1}}\mathbf{H}_{\mathrm{SI}}^{\mathrm{LOS}} + \sqrt{\frac{1}{\kappa+1}}\mathbf{H}_{\mathrm{SI}}^{\mathrm{NLOS}} \tag{13}$$

Bonus

The entries of the line-of-sight (LOS) contribution are modeled as [3]

$$\left[\mathbf{H}_{\mathrm{SI}}^{\mathrm{LOS}}\right]_{m,n} = \frac{\rho}{r_{m,n}} \exp\left(-\mathrm{j}2\pi \frac{r_{m,n}}{\lambda_c}\right) \tag{14}$$

where ρ is a normalization constant such that $\mathbb{E}\left[\|\mathbf{H}_{ii}\|_{\mathsf{F}}^2\right] = N_{\mathrm{t}} N_{\mathrm{r}}$ and $r_{m,n}$ is the distance from the mth element of the transmit array to the nth element of the receive array.

For the non-line-of-sight (NLOS) portion, we use the ray/cluster model (12).

Bonus

Algorithm 1: Hybrid beamforming decomposition when $N_{\mathrm{RF}} = 2N_{\mathrm{s}}$ and with infinite precision phase shifters [1].

Input: $\mathbf{F} \leftarrow$ desired beamformer
Output: $\mathbf{F}_{\mathrm{RF}}, \mathbf{F}_{\mathrm{BB}} \leftarrow$ analog and digital beamformers

$[N_{\mathrm{a}}, N_{\mathrm{s}}] = \mathsf{size}(\mathbf{F})$
$N_{\mathrm{RF}} = 2N_{\mathrm{s}}$
$\mathbf{F}_{\mathrm{RF}} = \mathrm{zeros}\,(N_a, N_{\mathrm{RF}})$
$\mathbf{F}_{\mathrm{BB}} = \mathrm{zeros}\,(N_{\mathrm{RF}}, N_{\mathrm{s}})$
for $k = 0 \ldots N_s - 1$ **do**
  $\mathbf{f} = [\mathbf{F}]_{:,k}$
  $v_{\max} = \max\,(\mathrm{abs}\,(\mathbf{f}))$
  for $i = 0 \ldots\ N_a\ -1$ **do**
    $b = \mathrm{abs}\,(\mathbf{f}(i))\,/(2v_{\max})$
    $\theta_1 = \angle\,(\mathbf{f}(i)) - \arccos(b)$
    $\theta_2 = \angle\,(\mathbf{f}(i)) + \arccos(b)$
    $\mathbf{F}_{\mathrm{RF}}(i, 2k-1) = \exp(\mathrm{j} \cdot \theta_1)$
    $\mathbf{F}_{\mathrm{RF}}(i, 2k) = \exp(\mathrm{j} \cdot \theta_2)$
    $\mathbf{F}_{\mathrm{BB}}(2k-1, k) = v_{\max}$
    $\mathbf{F}_{\mathrm{BB}}(2k, k) = v_{\max}$
  end
end
return $\mathbf{F}_{\mathrm{RF}}, \mathbf{F}_{\mathrm{BB}}$

Bonus

Algorithm 2: OMP-based hybrid approximation [2].

Input: $\mathbf{A}_{\mathrm{RF}} \leftarrow$ analog beamforming codebook matrix
Input: $\mathbf{F} \leftarrow$ desired fully-digital beamformer
Input: $N_{\mathrm{RF}} \leftarrow$ number of RF chains
Output: $\mathbf{F}_{\mathrm{RF}}, \mathbf{F}_{\mathrm{BB}} \leftarrow$ analog and digital beamformers

$[N_{\mathrm{a}}, N_{\mathrm{s}}] = \text{size}(\mathbf{F})$
$\mathbf{Y} = \mathbf{F}$
$\mathbf{Z} = [\ ]$
for $r = 0 \ldots N_{RF} - 1$ **do**
  $\mathbf{\Phi} = \mathbf{A}_{\mathrm{RF}}^{*} \mathbf{Y}$
  $k = \arg\max_{m} \left([\mathbf{\Phi}\mathbf{\Phi}^{*}]_{m,m} \right)$
  $\mathbf{Z} = \left[\mathbf{Z} \mid [\mathbf{A}_{\mathrm{RF}}]_{:,k} \right]$
  $\mathbf{F}_{\mathrm{BB}} = (\mathbf{Z}^{*}\mathbf{Z})^{-1} \mathbf{Z}^{*}\mathbf{F}$
  $\mathbf{Y} = \mathbf{F} - \mathbf{Z}\mathbf{F}_{\mathrm{BB}}$
  $\mathbf{Y} = \mathbf{Y} / \|\mathbf{Y}\|_{\mathsf{F}}$
end
$\mathbf{F}_{\mathrm{RF}} = \mathbf{Z}$
return $\mathbf{F}_{\mathrm{RF}}, \mathbf{F}_{\mathrm{BB}}$